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Intraoperative continuous vagus nerve monitoring with repetitive direct stimulation in surgery for jugular foramen tumors

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OBJECTIVE Surgery for tumors around the jugular foramen has significant risks of dysphagia and vocal cord palsy due to possible damage to the lower cranial nerve functions. For its treatment, long-term tumor control by maximum resection while avoiding permanent neurological damage is required. To accomplish this challenging goal, the authors developed an intraoperative continuous vagus nerve monitoring system and herein report their experience with this novel neuromonitoring method.

METHODS Fifty consecutive patients with tumors around the jugular foramen (34 jugular foramen schwannomas, 11 meningiomas, 3 hypoglossal schwannomas, and 2 others) who underwent microsurgical resection under continuous vagus nerve monitoring within an 11-year period were retrospectively investigated. Evoked vagus nerve electromyograms were continuously monitored by direct 1-Hz stimulation to the nerve throughout the microsurgical procedure.

RESULTS The average resection rate was 96.2%, and no additional surgery was required in any of the patients during the follow-up period (average 65.0 months). Extubation immediately after surgery and oral feeding within 10 days postoperatively were each achieved in 49 patients (98.0%). In 7 patients (14.0%), dysphagia and/or hoarseness were mildly worsened postoperatively at the latest follow-up, but tracheostomy or gastrostomy was not required in any of them. Amplitude preservation ratios on intraoperative vagus nerve electromyograms were significantly smaller in patients with postoperative worsening of dysphagia and/or hoarseness (cutoff value 63%, sensitivity 86%, specificity 79%).

CONCLUSIONS Intraoperative continuous vagus nerve monitoring enables real-time and quantitative assessment of vagus nerve function and is important for avoiding permanent vagus nerve palsy, while helping to achieve sufficient resection of tumors around the jugular foramen.

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KEYWORDS cerebellopontine angle; complication avoidance; craniocervical junction; jugular foramen neuroma; lower cranial nerve injury; skull base meningioma; oncology

Jugular foramen tumors frequently extend both intracranially and extracranially through the foramen, displacing or involving the lower cranial nerves that enter the jugular foramen. Resection of such tumors has critical risks of serious complications including hoarseness and dysphagia due to damage to vagus nerve functions, which can cause aspiration pneumonia and may require tracheostomy and gastrostomy after the surgery. Because many of the tumors around the jugular foramen, such as schwannomas and meningiomas, are clinically benign, long-term tumor control by maximum tumor resection while avoiding permanent neurological damage is required for their treatment. Recent advances in intraoperative neuromonitoring techniques have assisted in accomplishing this challenging goal.

In recent years, intraoperative vagus nerve monitoring to avoid postoperative dysphagia and vocal cord palsy has been reported.[1–3] However, conventional neuromonitoring techniques such as free-running spontaneous electromyography and occasional neural stimulation have critical disadvantages.[4–6] Free-running spontaneous electromyography can display the details of mechanical stimulation to the nerve in real time, but cannot quantitatively assess neural function. Occasional or intermittent neural stimula-

ABBREVIATIONS ROC = receiver operating characteristic.

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tion using a transcranial electrode or handheld probe enables quantitative assessment of neural function, but real-time alerts are not possible because this monitoring usually requires stopping of the microsurgical procedure. To overcome these disadvantages of conventional monitoring methods and to enable real-time and quantitative evaluation of neural function throughout the microsurgical procedure, we developed a novel monitoring method in which continuous 1-Hz stimulation directly to the proximal site (brainstem side) of the nerve is used.[6–9] This study aims to present our experience with intraoperative continuous vagus nerve monitoring and to analyze correlations between changes in the electromyograms and postoperative vagus nerve function.

Methods

The data of 50 consecutive patients with tumors around the jugular foramen (34 jugular foramen schwannomas, 11 meningiomas, 3 hypoglossal schwannomas, and 2 others) who underwent resection under intraoperative continuous vagus nerve monitoring by the senior author (M.K.) during an 11-year period (from 2009 to 2019) were retrospectively reviewed. These patients comprised 18 men and 32 women with a mean age of 42.0 years (range 14–76 years). During this 11-year period there were a total of 60 jugular foramen schwannoma surgeries, and continuous monitoring was performed efficiently in 34 of the 60 surgeries (56.7%; Fig. 1). The other 26 patients were excluded because of a lack of response due to severe preoperative neural damage (13 patients) or because continuous monitoring was not used due to easy dissection of the nerve from the tumor (13 patients).

The tumors were classified into the following 4 types: intradural tumor (type I, 10/50 patients, 20.0%); dumbbell-shaped tumor with intradural and intrajugular lesions (type IJ, 24/50 patients, 48.0%); triple dumbbell-shaped tumor with intradural, intrajugular, and extracranial lesions (type IJE, 13/50 patients, 26.0%); and triple dumbbell-shaped tumor with intradural, intrahypoglossal, and extracranial lesions (type IHE, 3/50 patients, 6.0%). The retrosigmoid approach was performed mostly for the intradural tumors (17/50 patients, 34.0%), and the retrosigmoid suprajugular approach was used when the tumor was mainly located intradurally, with partial extension into the upper jugular foramen (16/50 patients, 32.0%).[10,11] When the tumor occupied the entire jugular foramen or extended more significantly both intracranially and extracranially, particularly with an occluded or nondominant sigmoid sinus, the transmastoid transjugular approach with high cervical exposure was selected (13/50 patients, 26.0%).[12] The transcondylar approach with or without high cervical exposure was used for 3 hypoglossal schwannomas and 1 ventral foramen magnum neurenteric cyst (4/50 patients, 8.0%).[13]

Four patients had histories of previous resection and 1 patient underwent both surgery and Gamma Knife radiosurgery before our surgery. Preoperative dysphagia was observed in 13 of the 50 patients (26.0%), and hoarseness was observed in 11 patients (22.0%). In the detailed evaluation by otolaryngologists including fiber-optic laryngoscopy, preoperative laryngoparalysis was identified in 11 patients (22.0%). The extent of resection was evaluated by the surgeon's subjective evaluations, with careful confirmation on radiological images including enhanced MR images after the surgery. The patients' sex, age, lesion side, treatment history, preoperative dysphagia and/or hoarseness, preoperative laryngoparalysis, tumor size, tumor location, tumor resection rate, and amplitude preservation ratio on intraoperative vagus nerve electromyograms were compared between the patients with postoperative worsening of dysphagia and/or hoarseness and the others, using the Pearson chi-square and Wilcoxon rank-sum tests. Receiver operating characteristic (ROC) curves were plotted to calculate the most appropriate cutoff point, based on an optimal area under the curve, and to define the most clinically relevant combination of sensitivity and specificity. All statistical analyses were performed using JMP software (version 14.2.0; SAS Institute, Inc.), and p values less than 0.05 were considered to indicate a statistically significant difference between the two groups. Approval for this study was obtained from the institutional research ethics board.

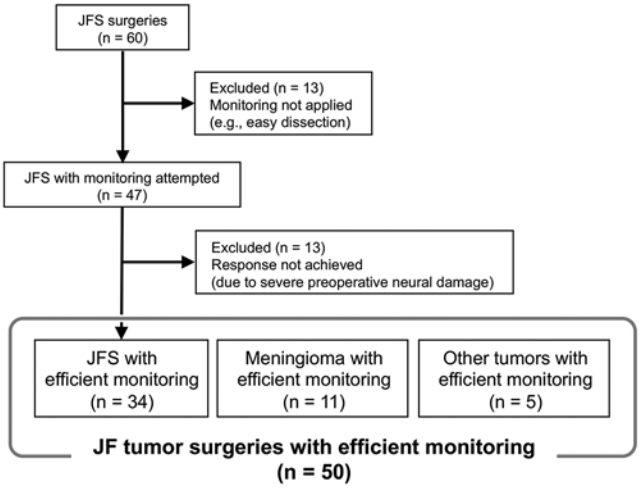

FIG. 1. Flowchart diagram of the patients included in this study. JFS = jugular foramen schwannoma.

Intraoperative Continuous Vagus Nerve Monitoring

Intraoperative continuous vagus nerve monitoring was performed together with monitoring of free-running spontaneous vagus nerve electromyograms and occasional vagus nerve stimulation applied using a handheld probe (Video 1).

VIDEO 1. Intraoperative continuous 1-Hz monitoring of evoked vagus nerve electromyograms. Copyright Ken Matsushima. Published with permission. Click here to view.

Electromyograms of the trigeminal, facial, accessory, and hypoglossal nerves; auditory brainstem response; and motor and somatosensory evoked potentials were also monitored during the surgery. The method used for vagus nerve monitoring was based on the method that we previously reported for facial nerve monitoring.[5]

After the induction of anesthesia and intubation, a re-

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cording monopolar needle (0.36-mm diameter; Gadelius Medical Co., Ltd.) was inserted into the lateral aspect of the soft palate on the tumor side using a laryngoscope or video laryngoscope. A reference electrode was placed on the patient's cheek on the healthy side. Both electrodes were placed by physicians. General anesthesia was maintained with total intravenous anesthesia without using neuromuscular blocking agents, except during the short period of anesthesia induction.

At the initial stage of tumor dissection, we always attempted to identify the vagus nerve proximal to the tumor (brainstem side) by using occasional stimulation with a handheld probe (5-Hz stimulation frequency; Medtronic Xomed, Inc.). We did the internal decompression of the tumor before starting the continuous monitoring, but only when the proximal vagus nerve was not identified in patients with a large tumor. After confirming an appropriate response, a 1.5-mm ball-type monopolar stimulating electrode (Unique Medical Co., Ltd.) was placed on the proximal vagus nerve and fixed using Surgicel (Ethicon) cotton balls to start the continuous monitoring. This ball-type electrode has been approved for electrocochleography but not for intracranial use, and therefore approval from the institutional review board and informed consent from all individual patients were obtained for its "off-label" use.

The maximum amplitude upon supramaximal stimulation (electrical intensity 0.1–3 mA, stimulation duration 0.2 msec) was recorded as the baseline response, and continuous monitoring was started with the lowest electrical stimulation (electrical intensity 0.2–0.8 mA) to evoke stable compound muscle action potentials. In addition, the minimum threshold of stimulation intensity that could evoke compound muscle action potentials was also recorded, which indicated the accuracy of the stimulating electrode placement. Evoked vagus nerve electromyograms were continuously monitored by 1-Hz direct stimulation using the ball-type electrode during the intradural procedure, with an electromyographic system (Neuropack, Nihon Kohden). The filter settings were 50 Hz (low bandpass) and 1 kHz (high bandpass). This monitoring enabled simultaneous quantitative monitoring of vagus nerve function every second without interrupting the microsurgical procedure. When a decrease in amplitude or a change in waveform was identified by technologists, the surgeon was informed immediately. This monitoring assisted in deciding the surgical strategy during tumor removal, in order to maximize tumor resection while minimizing postoperative neurological dysfunction. Complete tumor removal was attempted if the amplitude and waveform were sufficiently preserved, but partial tumor resection was considered when a significant decrease in amplitude was identified. The amplitude preservation ratio was calculated as the ratio of final maximum amplitude to baseline maximum amplitude, as follows: amplitude preservation ratio (%) = final maximum amplitude (μV)/baseline maximum amplitude (μV) × 100.

Dysphagia and hoarseness were each assessed clinically using a 4-grade scale (normal, mild, moderate, and severe), as follows: mild dysphagia, a sensation of difficulty in swallowing, with retained ability to swallow regular food and liquid; moderate dysphagia, a swallowing disturbance that necessitates a dysphagia diet; severe dysphagia, dysphagia that is severe enough to require tube feeding; mild hoarseness, mild voice changes but fully understandable; moderate hoarseness, moderate voice changes requiring occasional repetition; and severe hoarseness, severe voice changes causing difficulty in communication.

Results

On average, 96.2% (range 50%–100%) tumor removal was achieved, and less than 90% removal was performed in only 2 patients. Those individuals included an elderly patient with a triple dumbbell-shaped jugular foramen schwannoma, in whom only the intracranial component (evaluated as 50%) was resected via the retrosigmoid approach as preoperatively planned. In the other patient, who had a meningioma, a thin layer of the tumor was left behind (resection evaluated as 85%) because of strong adhesion to the lower cranial nerves.

Extubation was performed immediately after surgery in 49 of the 50 patients (98.0%), and on the next day in the remaining patient. Oral feeding was started after careful examination, including fiber-optic laryngoscopy by otolaryngologists, and was possible by 10 days after surgery in 49 patients (98.0%). A more detailed evaluation of the duration until oral feeding did not reflect the patients' symptoms, because it mainly depended on the fixed schedule of the otolaryngological examinations. Only 1 patient, who had a hypoglossal schwannoma with severe preoperative dysphagia, required 3 weeks before starting oral intake.

None of the patients required a tracheostomy, nasogastric tube management for nutrition, or gastrostomy, but worsening of dysphagia and/or hoarseness was seen in 7 of the 50 patients (14.0%, worsening group; Table 1) at the most recent follow-up (average 65.0 months). All of the patients in this group were graded as having mild dysfunction and now lead normal lives without requiring any additional treatment (e.g., thyroplasty) or a dysphagia diet. This group was composed of 6 patients with jugular foramen schwannoma and 1 patient with meningioma, and all the tumors had an intrajugular component. Of these 7 patients, 1 had a history of previous surgery and 1 had a history of both surgery and Gamma Knife radiosurgery. Therefore, 2 of the 5 patients (40.0%) with histories of previous treatment experienced worsening of dysphagia and/or hoarseness. Among these 7 patients, preoperative dysphagia and hoarseness were seen in 1 patient, and preoperative laryngoparalysis was seen in 3 patients. The patient with preoperative dysphagia and hoarseness experienced slight worsening of symptoms within the same grade (mild). Tumor size was not a statistically significant predictor of postoperative worsening of the symptoms. The resection rate was not statistically different in the two groups, although it was slightly higher in the worsening group.

With sufficient tumor removal, no additional resection was required in any of the patients during the follow-up period. Gamma Knife radiosurgery was required in 2 patients: in 1 patient with recurrent jugular foramen schwannoma that had rapidly regrown in only 2.5 years between the initial operation and our surgery, and in 1 patient with

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TABLE 1. Comparison between patients with and patients without postoperative worsening of dysphagia and/or hoarseness

Characteristic	Worsening Group	Nonworsening Group	p Value
No. of patients	7 (14.0%)	43 (86.0%)	
No. of females	3 (42.9%)	29 (67.4%)	0.209
Age in yrs (range)	32.0 (21–46)	43.7 (14–76)	0.032
Lesion on lt side	3 (42.9%)	21 (48.8%)	0.769
Treatment history, n = 5	2 (28.6%)	3 (7.0%)	0.077
Preop dysphagia/hoarseness, n = 14	1 (14.3%)	13 (30.2%)	0.384
Preop laryngoparalysis, n = 11	3 (42.9%)	8 (18.6%)	0.151
Tumor size in mm (range)	30.4 (14–46)	31.4 (11–59)	0.807
Tumor location			0.158
Type I; n = 10, 20.0%	0 (0%)	10 (23.3%)	
Type IJ; n = 24, 48.0%	3 (42.9%)	21 (48.8%)	
Type IJE; n = 13, 26.0%	4 (57.1%)	9 (20.9%)	
Type IHE; n = 3, 6.0%	0 (0%)	3 (7.0%)	
Pathology Dx of JFS, n = 34	6 (85.7%)	28 (65.1%)	0.279
Resection rate (range)	98.6% (97%–100%)	95.8% (50%–100%)	0.203
Amplitude preservation ratio (range)	41.7% (0%–89%)	80.0% (0%–100%)	0.003

Dx = diagnosis; JFS = jugular foramen schwannoma.

hypoglossal schwannoma with high expression of Ki-67 (approximately 30%–40%).

On average, the amplitude preservation ratio was 80.0% in the group with no postoperative worsening of symptoms and 41.7% in the group with worsening, and statistical analyses demonstrated that the amplitude preservation ratio was significantly smaller in the worsening group (Figs. 2–4). The ROC curve for the amplitude preservation ratio in the prediction of postoperative worsening of dysphagia and/or hoarseness identified an optimal cutoff point of 63% (sensitivity 86%, specificity 79%). There were no monitoring-associated complications, including bleeding or infection upon needle insertion into the soft palate, nor were there signs of nerve fatigue caused by repeated stimulation.

Discussion

Development of Vagus Nerve Monitoring Methods

Intraoperative vagus nerve monitoring was first attempted for preservation of the recurrent laryngeal nerve during neck dissection, particularly in thyroid surgery.[14] The methodology was adapted for neurosurgery, and free-run spontaneous electromyography and occasional stimulation were investigated to identify the course of the vagus nerve that was displaced or involved by the tumor, and to predict postoperative outcomes.[15–20] A few modifications, such as the use of transcranial stimulation and endotracheal tube surface recording electrodes, were also proposed.[19,21,22] In recent years, using occasional stimulation by transcranial stimulation and endotracheal tube recording, Ito et al.[1] and Fukuda et al.[2,3] reported that the amplitude preservation ratio was useful for predicting postoperative swallowing function. Occasional stimulation was also attempted during selective rhizotomy for the treatment of glossopharyngeal neuralgia.[23]

Development and Advantages of Continuous Monitoring With Repetitive Direct Stimulation

We first developed the continuous 1-Hz nerve monitoring technique for the facial nerve in 2005 for acoustic tumor surgery, which is more common than jugular foramen tumor surgeries.[5,6,24] After establishment of the continuous facial nerve monitoring technique, we carefully adopted the continuous 1-Hz monitoring technique to monitor motor function of the vagus nerve in the jugular foramen and craniocervical tumor surgeries, and have accumulated experience with this monitoring technique for more than 11 years.[6–9,11,25]

Recently, continuous vagus nerve monitoring has also been applied to more common thyroid surgeries, and its usefulness has been reported in many studies with sufficient numbers of cases.[26–30] Schneider et al.[26] compared continuous monitoring with intermittent monitoring in approximately 1000 at-risk nerves for each method during thyroid surgery and concluded that continuous monitoring resulted in fewer permanent vocal fold palsies, with higher sensitivity and specificity.

Our present study is the first to our knowledge that has applied continuous vagus nerve monitoring to neurosurgery and confirmed its high sensitivity and specificity in predicting postoperative vagus nerve palsy. Even in recent reports of the treatment of jugular foramen tumors by experienced surgeons, relatively high risks of severe postoperative dysphagia and/or hoarseness were reported, with some patients requiring tracheostomy or gastrostomy.[31–36] In the present study, based on this detailed neuromonitoring, only mild worsening of dysphagia and/or hoarseness was seen in 7 of the 50 patients, which did not disturb their normal lives postoperatively, and none of them required tracheostomy or gastrostomy.

Consecutive observation of free-running spontaneous

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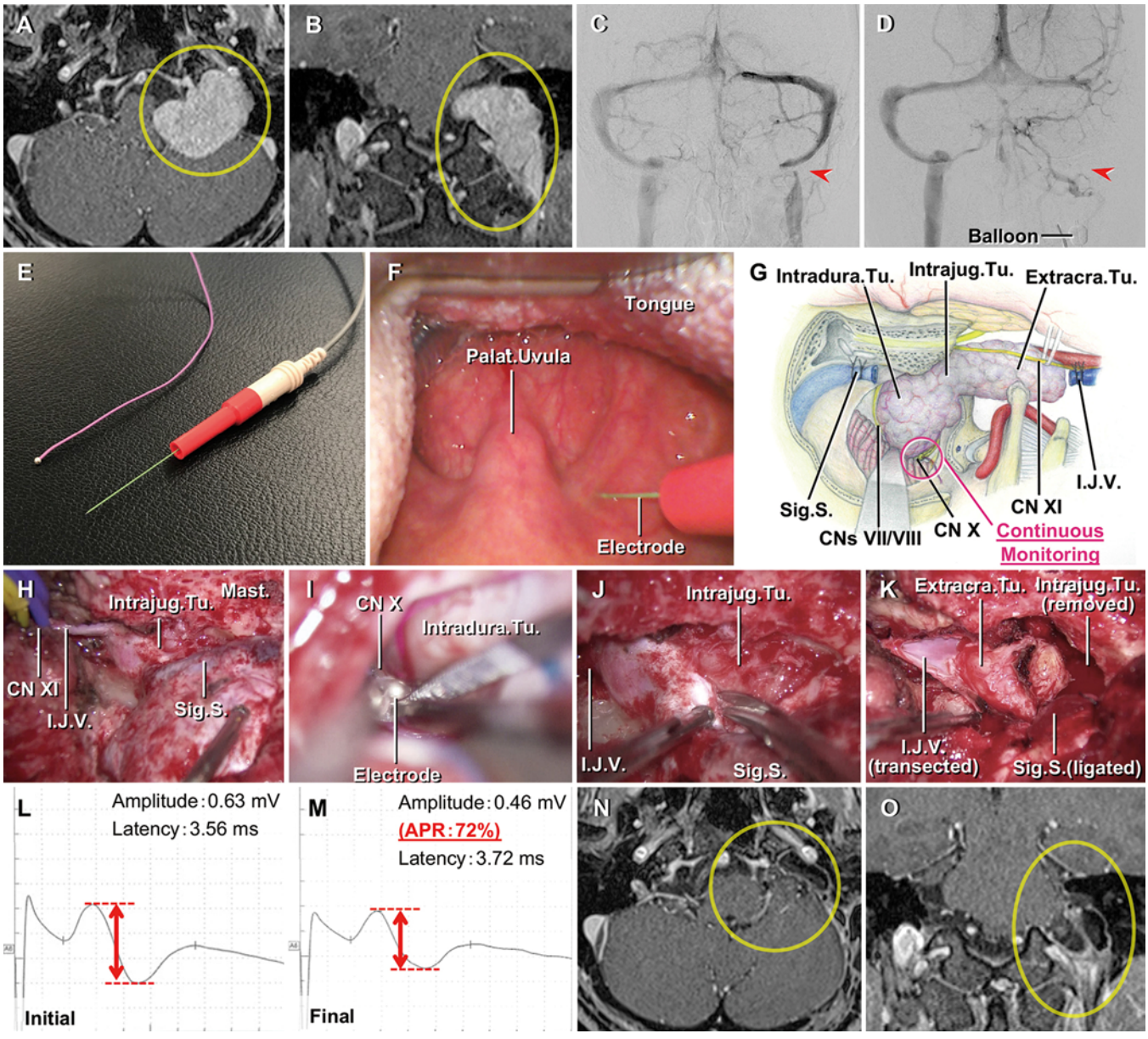

FIG. 2. A representative case without postoperative worsening of dysphagia and/or hoarseness. **A and B:** Preoperative enhanced MR images obtained in a woman in her 20s with hearing disturbance, displaying a left triple dumbbell-shaped tumor with intradural, intrajugular, and extracranial lesions (*yellow circles*). **C:** Preoperative angiograms revealed that the sigmoid sinus was stenosed by the tumor but was still patent (*red arrowhead*). **D:** The 20-minute balloon occlusion test confirmed a good contralateral venous drainage without causing any neurological deficits, which predicted the safety of the sinus ligation. The occluded sigmoid sinus is indicated by a *red arrowhead*. **E:** A monopolar needle that was placed preoperatively on the soft palate for recording, and a 1.5-mm ball-type monopolar electrode that was placed on the proximal site of the vagus nerve at the initial stage of the tumor dissection for repetitive stimulation. **F:** A laryngoscopic picture demonstrating insertion of the monopolar needle into the soft palate before the surgery. **G:** An illustration demonstrating the transmastoid transjugular approach with high cervical exposure under the continuous vagus nerve monitoring. Modified with permission from Matsushima K, Kohno M. [High-speed drills in skull base approaches]. In: Morita ed. *NS NOW Updated Skills to be Learned by Neurosurgical Specialists.* Tokyo: Medical View Co., Ltd.; 2020. pp 44–53. (Jpn).[25] H–K: Intraoperative photographs. **H:** The sigmoid-jugular venous drainage was completely exposed. **I:** Before starting removal of the intradural tumor, the ball-type monopolar electrode was placed on the proximal site of the vagus nerve and continuous 1-Hz monitoring was started. **J:** After ligation of the sigmoid sinus and internal jugular vein, the intrajugular tumor was resected. **K:** The extracranial tumor was also removed to accomplish total tumor removal. **L and M:** Evoked vagus nerve electromyograms were monitored continuously, and the amplitude preservation ratio was 72%, resulting in no permanent dysphagia or hoarseness. **N and O:** Enhanced MR images obtained 40 months after surgery confirmed complete resection of the tumor and no signs of recurrence (*yellow circles*). APR = amplitude preservation ratio; CN = cranial nerve; Extracra. = extracranial; I.J.V. = internal jugular vein; Intradura. = intradural; Intrajug. = intrajugular; Mast. = mastoid; Palat. = palatine; Sig.S. = sigmoid sinus; Tu. = tumor. Figure is available in color online only.

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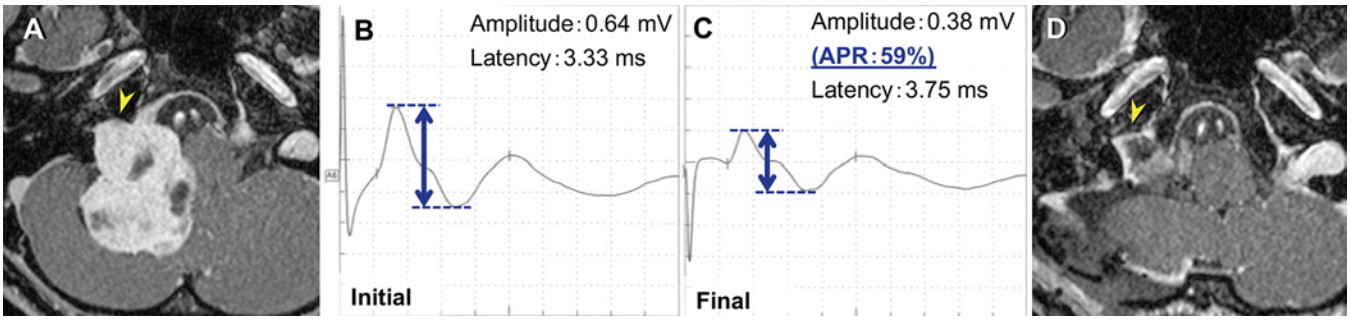

FIG. 3. A representative case with postoperative worsening of dysphagia and/or hoarseness. **A:** Preoperative enhanced MR images obtained in another woman in her 20s with hearing disturbance displayed a right jugular foramen schwannoma extending into the upper jugular foramen (*yellow arrowhead*). **B and C:** Evoked vagus nerve electromyograms were monitored continuously during the retrosigmoid suprajugular approach. A decrease in amplitude was identified during the microsurgical procedure, and hence we decided to leave a thin layer of the tumor that was strongly adhered to the lower cranial nerves (resection rate 98%). The amplitude preservation ratio was 59%, and the patient had mild worsening of dysphagia at the latest follow-up. **D:** Postoperative enhanced MR images did not display any remnant tumor including the intrajugular component (*yellow arrowhead*). APR = amplitude preservation ratio. Figure is available in color online only.

electromyograms demonstrates the mechanical stimulation to the nerve in real time, without stopping the microsurgical procedure. Several studies investigated this method in detail for its efficacy in predicting postoperative neural functions, but it is difficult to quantitatively assess the degree of damage to the nerve by using this method.[15,37] Occasional or intermittent neural stimulation enables the quantitative assessment of neural function, but frequent stimulation (e.g., every second) during the microsurgical procedure is impossible, so the surgeon cannot receive real-time alerts. Our novel continuous 1-Hz monitoring technique overcame these disadvantages of the two aforementioned conventional monitoring methods and enables real-time and quantitative evaluation of neural function throughout microsurgical procedures.[4–6] The real-time alert at the moment of the waveform change enables surgeons to stop the risky procedure and prevent critical neural damage. Furthermore, quantitative evaluation helps surgeons to decide on an intraoperative surgical strategy, i.e., whether to complete total tumor removal or only perform subtotal removal of the tumor.

Transcranial stimulation is another option for electri-

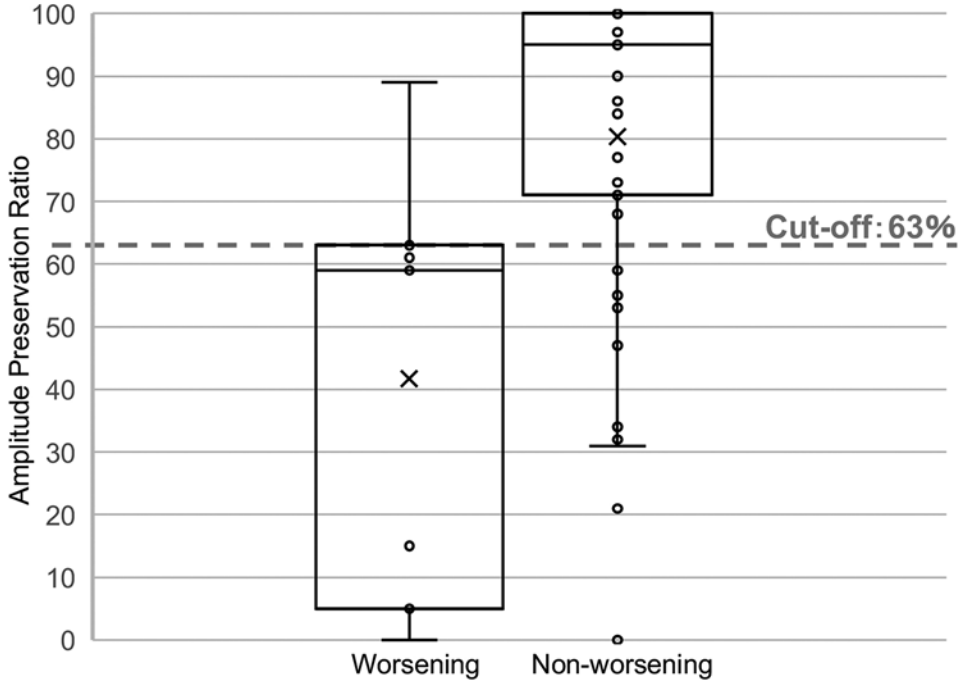

FIG. 4. Comparison of amplitude preservation ratios between patients with and patients without postoperative worsening of dysphagia and/or hoarseness. Amplitude preservation ratios of intraoperative vagus nerve electromyograms were significantly smaller in the patients with postoperative worsening of dysphagia and/or hoarseness. The most appropriate cutoff was 63% by ROC analysis (*dotted line*).

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cal stimulation, but there is a problem of body movement when applying the continuous 1-Hz stimulation, because transcranial stimulation requires a larger current than direct neural stimulation. It is generally recommended that microsurgical procedures be stopped at the moment of transcranial stimulation, from the viewpoint of safety. In addition, if transcranial stimulation is applied for continuous monitoring, the safety of such frequent stimulations with a larger current (e.g., excitotoxic injury or epileptogenic effect) has not been clarified.[38] Recent reports have demonstrated the use of an endotracheal tube with surface electrodes to record electromyograms of the recurrent laryngeal nerve;[1–3,17–19,21,22,39] however, we prefer using a needle electrode inserted into the soft palate to record the pharyngeal branch of the vagus nerve, because in our experience its larger amplitude enables more sensitive measurements during surgery. In addition, postoperative edema of the vocal cords caused by their compression by endotracheal tube surface electrodes was previously reported.[39] Muscles forming the soft palate are innervated by the mandibular nerve (tensor villi palatini) and the pharyngeal plexus formed by fibers from the lower cranial nerves. Because most of these muscles except for the stylopharyngeus muscle (glossopharyngeal nerve) are innervated mainly by the vagus nerve, responses of the glossopharyngeal nerve stimulation are usually too low to monitor consistently and quantitively, and the vagus nerve stimulation can provide more stable electromyograms, as several authors have reported.[17,20]

Disadvantages of Continuous Monitoring and Study Limitations

This continuous monitoring method has several disadvantages to be mentioned. First, assessment of the data taken every second and control of the monitoring require considerable experience. For large lesions, initial internal decompression of the tumor is sometimes required before identifying the proximal site (brainstem side) of the vagus nerve. Therefore, until the nerve is identified and continuous monitoring is started, we routinely monitor the nerve by free-running electromyography to avoid damage. Quantitative analysis by transcranial intermittent stimulation can also be used until the start of continuous monitoring. Another concern is that the proximal vagus nerve cannot be identified in some cases, especially in jugular foramen schwannomas. However, in our experience the vagus nerve could not be identified in only 2 of the 60 surgeries for jugular foramen schwannomas. In these 2 schwannomas, the tumors were suspected to originate from the vagus nerve.

Because stable placement of the recording electrode on the nerve may be difficult throughout the entire tumor removal procedure, we introduced techniques and tips for stable electrode placement using Surgicel cotton balls and small cotton pads in our previous reports.[4,40] The wire of the electrode should also be moved away from the surgical field by cotton pads, as shown in our previous video.[11] In the 13 surgeries for jugular foramen schwannomas, we were unable to achieve a sufficient response even after appropriate stimulation, due to the patients' severe preoperative neural damage. For such cases, future development of other neuromonitoring methods without using electromyograms may be required. Even with our accumulation of experience over 11 years, our sample size was still small because of the rarity of surgeries for tumors around the jugular foramen, and hence the data are not suitable for more detailed statistical analysis. Further clinical experience is required to solidify the safety and efficacy of this continuous vagus nerve monitoring technique.

Conclusions

Intraoperative continuous vagus nerve monitoring with repetitive direct stimulation enables real-time and quantitative assessment of neural function without interrupting microsurgical procedures. The amplitude preservation ratio significantly correlated with postoperative vagus nerve function. Detailed neuromonitoring is essential to achieve sufficient tumor resection while avoiding permanent vagus nerve palsy in jugular foramen and craniocervical tumor surgeries.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Kohno, Matsushima. Acquisition of data: Kohno, Matsushima, Nakajima, Yoshino. Analysis and interpretation of data: Matsushima, Ichimasu, Tanaka. Drafting the article: Matsushima. Critically revising the article: Kohno. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Kohno. Statistical analysis: Matsushima, Ichimasu, Tanaka. Study supervision: Kohno.

Supplemental Information

Videos

Video 1. https://vimeo.com/463136637.

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